

## MASS FLOW RATIO SYSTEM AND METHOD

### Field of Disclosure

(01) The present disclosure relates generally to semiconductor processing equipment and, more particularly, to systems, devices, and methods for delivering contaminant-free, precisely metered quantities of process gases to semiconductor process chambers. Even more particularly, the present disclosure relates to a system and method for dividing a single mass flow into a desired ratio of two or more flows.

### Background of Disclosure

(02) The fabrication of semiconductor devices often requires the careful synchronization and precisely measured delivery of as many as a dozen gases to a process chamber. Various recipes are used in the fabrication process, and many discrete processing steps, where a semiconductor device is cleaned, polished, oxidized, masked, etched, doped, metalized, etc., can be required. The steps used, their particular sequence, and the materials involved all contribute to the making of particular devices.

(03) Accordingly, wafer fabrication facilities are commonly organized to include areas in which chemical vapor deposition, plasma deposition, plasma etching, sputtering and other similar gas manufacturing processes are carried out. The processing tools, be they chemical vapor deposition reactors, vacuum sputtering machines, plasma etchers or plasma enhanced chemical vapor deposition, must be supplied with various process gases. Pure gases must be supplied to the tools in contaminant-free, precisely metered quantities.

(04) In a typical wafer fabrication facility the gases are stored in tanks, which are connected via piping or conduit to a gas box. The gas box delivers contaminant-free, precisely metered quantities of pure inert or reactant gases from the tanks of the fabrication facility to a process tool. The gas box, or gas metering system includes a plurality of gas paths having gas

metering units, such as valves, pressure regulators and transducers, mass flow controllers and filters/purifiers. Each gas path has its own inlet for connection to separate sources of gas, but all of the gas paths converge into a single outlet for connection to the process tool.

(05) Sometimes dividing the combined process gases equally among multiple process chambers, or among separate portions of a single process chamber, is desired. In such cases, the single outlet of the gas box is connected to secondary flow paths. To insure that the primary flow of the outlet of the gas box is divided equally among the secondary flow paths, flow restrictors are placed in each secondary flow path.

(06) What is still desired, however, is a mass flow ratio system and method for dividing a single flow into a desired ratio of two or more flows. Preferably, the system and method will operate independently of the gas or gases controlled. In addition, the system and method preferably will not disturb the performance of any upstream mass flow controllers.

#### Summary of Disclosure

(07) Accordingly, the present disclosure provides a system for dividing a single mass flow into two or more secondary mass flows of desired ratios. The system includes an inlet adapted to receive the single mass flow and at least two secondary flow lines connected to the inlet. Each flow line includes a flow meter measuring flow through the flow line and providing a signal indicative of the measured flow, and a valve controlling flow through the flow line based upon receiving a signal indicative of desired flow rate.

(08) The system also includes a user interface adapted to receive at least one desired ratio of flow, and a controller connected to the flow meters, the valves, and the user interface. The controller is programmed to receive the desired ratio of flow through the user interface, receive the signals indicative of measured flow from the flow meters, calculate an actual ratio of flow through the flow lines based upon the measured flow, and compare the actual ratio to the desired ratio. The controller is also programmed to calculate the desired flow through at least

one of the flow lines if the actual ratio is unequal to the desired ratio, and provide a signal indicative of the desired flow to at least one of the valves.

(09) The present disclosure also provides a method for dividing a single mass flow into two or more secondary mass flows of desired ratios. The method includes dividing a single mass flow into at least two secondary flow lines, measuring mass flow through each flow line, receiving at least one desired ratio of mass flow, and calculating an actual ratio of flow through the flow lines based upon the measured flows. If the actual ratio does not equal the desired ratio, the method also includes calculating a desired flow through at least one of the flow lines, and regulating the actual flow in that flow line to the desired flow.

(10) The system and method of the present disclosure provide the benefit of operating independently of the gas or gases controlled. In addition, the system and method do not disturb the performance of any upstream mass flow controllers.

(11) These and other features and advantages of the present disclosure will become more apparent to those of ordinary skill in the art after reading the following detailed description of the preferred embodiments, which are illustrated in the attached drawing figures.

#### Brief Description of Drawings

(12) Fig. 1 is a schematic illustration of a mass flow ratio system constructed in accordance with the present disclosure, and shown connected between a gas metering box and two process chambers;

(13) Fig. 2 is a flow chart of a method for dividing flow for the system of Fig. 1;

(14) Figs. 3 and 4 are graphs illustrating mass flow ratio control ranges of the system and method of Figs. 1 and 2 for different minimum flows;

(15) Fig. 5 is a table illustrating an exemplary embodiment of a user interface connection for the system of Fig. 1;

(16) Fig. 6 is a schematic illustration of another mass flow ratio system constructed in accordance with the present disclosure, and shown connected between a gas metering box and multiple portions of a process chamber;

(17) Fig. 7 is a schematic illustration of two flow paths constructed in accordance with the prior art and connected between a gas metering box and two process chambers; and

(18) Fig. 8 is a schematic illustration of an existing mass flow divider connected between a gas metering box and two process chambers.

(19) Like reference characters designate identical or corresponding components and units throughout the several views.

#### Detailed Description of Disclosure

(20) Referring to Figs. 1 and 2, the present disclosure provides a mass flow ratio system 10 and method 12 for dividing a single mass flow into a desired ratio of two or more mass flows. The system 10 and method 12 are particularly intended for use with gas metering systems for delivering contaminant-free, precisely metered quantities of process and purge gases to semiconductor process chambers. The presently disclosed system 10 and method 12 provide the benefit of operating independently of the gas or gases controlled, and of operating without disturbing the performance of any upstream mass flow controllers.

(21) Referring first to Fig. 7, however, an existing system 100 for dividing flow according to the prior art is shown for comparison. The system 100 is incorporated in a gas metering system 102 that receives multiple gases, including both process gases and a purge gas, from gas supplies (e.g., gas tanks) 104a, 104b, 104c, 104d and then precisely meters the gases to two process chambers 106, 108 (alternatively, the gases can be metered to different injectors or

areas of a single process chamber). The gas metering system 102 includes a gas box 110 having a plurality of gas sticks 112a, 112b, 112c, 112d (while four sticks are shown, the gas box can include more or less than four).

(22) Each stick includes, for example, a mass flow controller (MFC) 114, a valve 116 positioned before the MFC and a valve 118 positioned after the MFC. The gas sticks 112a, 112b, 112c, 112d are separately connected to the gas sources 104a, 104b, 104c, 104d and provide controllable gas passageways so that a contaminant-free, precisely metered amount of a gas, or combination of gases, can be supplied from the gas metering system 102 to the process chambers 106, 108. Although not shown, the sticks 112a, 112b, 112c, 112d can also each be provided with other components for monitoring or controlling gases, such as filters, purifiers, and pressure transducers and controllers. The sticks 112a, 112b, 112c, 112d connect together, in an outlet manifold 128 for example, to allow the gas flows from each stick to be mixed if desired prior to leaving the gas box.

(23) A vacuum pump 120 is connected to the process chambers 106, 108 through gate valves 122, 124. During operation, the vacuum pump 120 draws gas from the gas sources 104a, 104b, 104c, 104d, through the gas metering system 102 and into the process chambers 106, 108.

(24) The prior art system 100 for dividing flow between the at least two process chambers 106, 108 includes an inlet manifold, or line 126 connected to the outlet manifold 128 of the gas box 110, first and second flow lines 130, 132 extending from the inlet 126 to the process chambers 106, 108, and restrictors 134 placed in each flow line. In order to accurately control the flow rates through the first and the second lines 130, 132, the smallest cross-sectional flow area (e.g., diameter) of the restrictors 134 must be larger than any other restrictions in the first and the second flow lines 130, 132. Because restrictors 134 are used to control the flow rates, the upstream pressure (i.e., the pressure of the gas delivery system 102 prior to the flow dividing system 100) must be kept relatively high (e.g., 30 to 40 PSIA). Thus, in situations where it is preferable to keep the upstream pressure relatively low (e.g., 15 PSIA or less), for

safety or other reasons, the system 100 of the prior art is not accurate in dividing and regulating flow. Furthermore, it is not possible to change the flow ratios between the flow lines 130, 132 without changing the restrictors 134, which can cause system downtime.

(25) Referring to Fig. 8, an existing flow dividing system 210 is shown. The system 210 is described in greater detail in co-pending U.S. patent application serial number 09/836,748, filed April 17, 2001, which is assigned to the assignee of the present invention and incorporated herein by reference (attorney docket number MKS-86). The system 210 includes an inlet line or manifold 212 for receiving the single gas flow from the outlet manifold 128 of the gas box 110, and first and second flow lines 214, 216 connected to the inlet 212. A mass flow meter 218 measures gas flow through the first line 214 and provides a signal indicative of the measured flow rate. A restrictor 220 restricts gas flow through the first line 214 to a desired flow rate, and has a smallest cross-sectional flow area selected to provide an upstream pressure high enough to allow the mass flow meter 218 to operate properly and lower than a predetermined upper pressure limit. The system also has a mass flow controller 222 controlling gas flow through the second line 216. The mass flow controller 222 receives the signal indicative of the measured flow rate from the mass flow meter 218 and maintains a flow rate through the second line 216 based on the signal.

(26) Preferably, the smallest cross-sectional flow area of the restrictor 220 is selected such that the predetermined upper pressure limit is equal to about 15 PSIA. In addition, the mass flow meter 218 and the mass flow controller 222 are preferably provided with the same flow range. In the flow dividing system 210 of Fig. 8, the mass flow controller 222 maintains a flow rate through the second line 216 substantially equal to the measured flow rate of the first line 214. Although not shown, the flow divider system 210 can be provided with a controller for proportionally adjusting the signal indicative of the measured flow rate from the mass flow meter 218 prior to the signal being received by the mass flow controller 222, such that the mass flow controller 222 maintains a flow rate through the second line 216 substantially equal to a

predetermined ratio of the measured flow rate of the first line 214. The system 210 is provided as a modular unit for quick and easy assembly between a gas box and a process chamber(s), and includes a shut-off valve or suitable connector 250 between the inlet manifold 212 of the system 210 and the outlet manifold 128 of the gas box 110

(27) Referring again to Fig. 1, the presently disclosed mass flow ratio system 10 includes an inlet line or manifold 12 for receiving the single gas flow from the outlet manifold 128 of the gas box 110, and first and second flow lines 14a, 14b connected to the inlet 12. Each line 14a, 14b is provided with a mass flow meter 18a, 18b measuring mass flow through the line and providing a signal indicative of the measured flow, and a valve 20a, 20b controlling flow through the line based on a signal indicative of a desired flow rate. The ratio system 10 also has a user interface 22 for receiving a desired flow ratio, and a controller 24 connected to the flow meters 18a, 18b, the valves 20a, 20b and the user interface 22. The flow ratio " $\alpha$ " is defined herein as the flow " $Q_2$ " through the second line 14b divided by the flow " $Q_1$ " through the first line 14a.

(28) Referring also to Fig. 2, the controller 24 is programmed to receive the desired ratio of flow through the user interface 22, as shown at 30, receive the signals indicative of measured flow from the flow meters 18a, 18b, as shown at 32, calculate an actual ratio of flow through the flow lines 14a, 14b based upon the measured flow, as shown at 34, and compare the actual ratio to the desired ratio, as shown at 36. The controller 24 is also programmed to calculate the desired flow through at least one of the flow lines 14a, 14b if the actual ratio is unequal to the desired ratio, as shown at 38, and provide an "adjustment" signal indicative of the desired flow to at least one of the valves 20a, 20b, as shown at 40. The controller 24, therefore, adjusts flow through at least one of the flow lines 14a, 14b until the actual ratio of flow through the lines equals the desired ratio.

(29) In a preferred embodiment, the controller 24 is programmed to provide an "initial" signal to the valve 20a of the first line 14a indicative of a first desired flow, calculate a

second desired flow if the actual flow ratio is unequal to the desired flow ratio, and provide an "adjustment" signal to the valve 20b of the second flow line 14b indicative of the second desired flow. The "adjustment" signal is calculated by

$$V_{c2} = K_{pa}(\alpha - \alpha_{sp}) + K_{ia}\int(\alpha - \alpha_{sp})dt$$

(30) Wherein  $V_{c2}$  is the command from the controller 24 to the second valve 20b,  $K_{pa}$  is a proportional gain for the ratio control,  $K_{ia}$  is an integral gain for the ratio control,  $\alpha$  is the measured flow ratio, and  $\alpha_{sp}$  is the ratio set point or desired flow ratio. In this manner, the valve 20a of the first line 14a acts as a fixed orifice, while the valve 20b of the second line 14b acts as a variable control valve. This feature allows the system 10 to operate independently of the type of gas(es) controlled through the system, since errors in flow measurement due to differing gases are the same for both flow meters 18a, 18b. Preferably, the controller 24 is programmed to cause the valve 20a of the first line 14a to fully open, such that the overall pressure drop across the system 10 is minimized.

(31) Examples of suitable mass flow meters 18a, 18b for use with the ratio system 10 of the present disclosure are thermally based Mass-Flo<sup>®</sup> brand controllers available from the assignee of the present disclosure, MKS Instruments of Andover, MA (<http://www.mksinst.com>). Suitable valves 20a, 20b are also available from the assignee. The valves 20a, 20b are non-linear and have a narrow controllable range. The thermal flow meters 18a, 18b, however, are the limiting factor in determining a control range provided by the system 10, since the flow meters are not normally reliable below five percent of the maximum sensor range (e.g., a 2,000 sccm thermal flow meter is not reliable below 100 sccm). Figs. 3 and 4 are graphs illustrating ratio control ranges of a system 10 constructed in accordance with the present disclosure, based on the limiting range of the thermal flow meters. The graph of Fig. 3 is for a minimum flow rate ("Qmin") of 100 sccm through the system 10, while the graph of Fig. 4 is for



a minimum flow rate of 200 sccm. Both graphs are based upon a flow of Nitrogen ( $N_2$ ), and include plots for three gas correction factors ("GCF"); 0.5, 1.0, and 1.4.

(32) Fig. 5 is a table illustrating an exemplary embodiment of a connector of the user interface 22 for the flow ratio system 10 of Fig. 1. As shown, the connector comprises a 15 pin D connector, and the assignments and description for each pin are suggested. Although not shown, the controller 24 may include a microprocessor, memory, an electronic clock oscillator, an analog to digital converter and a multiplexer, for example.

(33) Referring to Fig. 6, another mass flow ratio system 50 constructed in accordance with the present disclosure is shown. The systems 10 and 50, respectively, of Figs. 1 and 6 are similar, and elements that are the same have the same reference characters. The system 50 of Fig. 6 further includes a third flow line 14c connected to the inlet 12, and a mass flow meter 18c measuring mass flow through the line 14c and providing a signal indicative of the measured flow, and a valve 20c controlling flow through the line 14c based on a signal indicative of a desired flow rate. As shown, the three lines 14a, 14b, 14c of the system 30 can be connected to three portions of a single process chamber 106.

(34) In the embodiment of Fig. 5, the user interface 24 is preferably adapted to receive a desired ratio of flow for the second and the first flow lines 14b, 14a, and a desired ratio of flow for the third and the first flow lines 14c, 14a (i.e., " $\alpha_1$ " = " $Q_2$ " / " $Q_1$ " and " $\alpha_2$ " = " $Q_3$ " / " $Q_1$ "). The controller 24 is programmed to provide a signal to the valve 20a of the first line 14a indicative of a first desired flow, thereby making the valve 20a a fixed orifice. Preferably, the valve 20a is fully opened. The controller 24 then receives the desired ratios of flow through the user interface 22, receives the signals indicative of measured flow from the flow meters 18a, 18b, calculates an actual ratio of flow for the second and the first flow lines 14b, 14a based upon the measured flows through the second and the first flow lines, calculates a second desired flow if the actual ratio for the second and the first flow lines is unequal to the desired ratio for the

second and the first flow lines, and provides a signal to the valve 20b of the second flow line 14b indicative of the second desired flow.

(35) The controller 24 is also programmed to calculate an actual ratio of flow for the third and the first flow lines 14c, 14a based upon the measured flows through the third and the first flow lines, calculate a third desired flow if the actual ratio for the third and the first flow lines is unequal to the desired ratio for the third and the first flow lines, and provide a signal to the valve 20c of the third flow line indicative of the third desired flow. The valves 20b, 20c of the second and third lines 14b, 14c, therefore, act as control valves with respect to the valve 20a of the first line 14a.

(36) Although not shown, the mass flow ratio systems 10, 30 can be provided with more than three flow lines 14, with each additional flow line having a valve 20 and a flow meter 18 connected to the controller 24. In addition, it is envisioned that a mass flow controller can be used as the mass flow meter and the valve of each line. Although not shown, it is envisioned that the disclosed ratio systems 10, 30 can be provided as a modular unit for quick and easy assembly between a gas box and a process chamber(s). In such a case, a shut-off valve or suitable connector 50 might be provided between the inlet manifold 12 of the ratio systems 10, 30 and the outlet manifold 128 of the gas box 110, as shown in Figs. 1 and 5.

(37) Embodiments of a system and a method for dividing flow according to the present invention can further include a pressure sensor for the inlet 12 and/or outlets of the system 10. The inlet pressure and/or the outlet pressure measurement provided by the pressure sensor(s) is used by the controller 24 to not only control the ratio " $\alpha$ " of the flows, but also control the inlet pressure and/or the outlet pressures.

(38) Adding a pressure control feature has a number of ancillary benefits, including improving the system 10 performance and reducing disturbances to devices upstream or downstream of the system 10. By operating the system 10 at the maximum allowable pressures,

the need for factors of safety in the ratio control system can be removed or reduced. In addition, controlling the pressure drop across the valves 20a, 20b improves valve performance and makes valve setup, matching, and tuning more simple. The present disclosure is intended, therefore, intended to include a system and a method for dividing flow, with any added pressure control features. For example, the present disclosure is intended to include the flow divider system 10 plus a pressure sensor(s) in the inlet and/or the outlets of the system. The present disclosure is also intended to include a method 12 of dividing flow plus measuring pressure(s) in the inlet and/or the outlets. In effect, the present application is meant to include any control methodologies using pressure measurements for the claimed flow dividing system and method.

(39) The following example is made with reference to Fig. 1. Assuming the addition of a pressure sensor (not shown) on the inlet 12 of the mass flow ratio system 10, the controller 24 is programmed to take three inputs: the flow "Q<sub>2</sub>" through the second line 14b; the flow "Q<sub>1</sub>" through the first line 14a; and a measured pressure "P<sub>in</sub>" at the inlet 12 as provided by the pressure sensor. The controller 24 is programmed to issue commands to both of the first and the second valves 20a, 20b dynamically, instead of just controlling one valve at a time. However, in terms of ratio control, the "fixed valve" is mostly open, while the ratio is determined by controlling the other valve between 10% and 50% of a control range of the valve. With the addition of the pressure signal the fixed valve is set to control the inlet pressure, and the other valve is used to control the flow ratio. An example of an inlet pressure control could be written as:

$$V_{c1} = K_{pa}(\alpha - \alpha_{sp}) + K_{ia} \int (\alpha - \alpha_{sp}) dt$$

$$V_{c2} = K_{pp}(P_{in} - P_t) + K_{ip} \int (P_{in} - P_t) dt$$

(40) Wherein V<sub>c1</sub> is the command from the controller 24 to the first valve 20a, and V<sub>c2</sub> is the command to the second valve 20b, K<sub>pp</sub> is a proportional gain for pressure control, K<sub>ip</sub> is an

integral gain for the pressure control,  $K_{pa}$  is a proportional gain for the ratio control,  $K_{ia}$  is an integral gain for the ratio control,  $\alpha$  is the measured flow ratio,  $\alpha_{sp}$  is the ratio set point or desired flow ratio,  $P_{in}$  is the measured inlet pressure, and  $P_t$  is an operating pressure threshold (or a desired pressure).

(41) While the control system and method is described as a proportional-plus-integral (PI) type control system and method, it should be appreciated that other types of control systems and methods can be used, such as proportional, integral, proportional-plus-derivative (PD), and proportional-plus-integral-plus-derivative (PID) types of control systems and methods.

(42) While there have been illustrated and described particular embodiments of the present disclosure, it will be appreciated that numerous changes and modifications will occur to those skilled in the art. Accordingly, it is intended that the appended claims cover all those changes and modifications which fall within the true spirit and scope of the present disclosure.